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Neutron Electric Dipole Moment Experiments

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The neutron electric dipole moment (EDM) provides unique information on CP violation and physics beyond the Standard Model. We first review the history of experimental searches for neutron electric dipole moment. The status of future neutron EDM experiments, including experiments using ultra-cold neutrons produced in superfluid helium, will then be presented.

Keywords: CP violation; Neutron EDM; Ultra-cold neutrons

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1. Introduction

The possibility of a non-zero value for neutron EDM continues to be of central importance in physics and cosmology. A non-zero neutron EDM would be a direct evidence for time-reversal symmetry violation. It also implies CP-violation under the assumption of CPT invariance. To date, only two examples of CP-violation have been found: decays of neutral K mesons and B mesons. CP-violation is believed to have occurred during the Big Bang baryogenesis that led to the present matter-antimatter asymmetry in the Universe. Although CP-violation observed in K and B meson decays can be incorporated phenomenologically within the Standard Model, the strength of the effect is not large enough to explain the matter-antimatter asymmetry. It is likely that a full description of CP-violation would invoke non-standard models, many of which predict a neutron EDM large enough to be accessed experimentally¹. Therefore, a sensitive measurement of the neutron EDM is of fundamental interest since it could identify new sources of CP-violation as well as physics beyond the Standard Model.

In this article, we first review the history of neutron EDM experiments. The prospect for future neutron EDM experiments will then be presented. In particular, the status of proposed experiments using ultra cold neutrons at various laboratories will be discussed.

2. Existing Neutron EDM Experiments

The history of neutron EDM measurements is closely connected to the development of our knowledge on discrete symmetries in physics. In 1950, when parity was considered as an inviolable symmetry, Purcell and Ramsey² pointed out the need to test this symmetry via a detection of neutron EDM. They then carried out a pioneering experiment^{3,4} setting an upper limit at $5 \times 10^{-20} e \cdot cm$ for neutron EDM. The role of baryon (proton, neutron, hyperons) EDM in testing parity symmetry was extensively discussed in the seminal paper of Lee and Yang⁵, who cited the yet-unpublished neutron EDM result from Smith, Purcell, and Ramsey^{3,6}.

The discovery of parity violation in 1957⁷ prompted Smith et al. to publish their neutron EDM result⁴. By this time, however, it was recognized^{8,9} that time-reversal invariance would also prevent the neutron from possessing a non-zero EDM. Since no evidence of T-violation was found even in systems which exhibited maximal parity violation, a non-zero neutron EDM was regarded as highly unlikely. The experimental activities on neutron EDM therefore lay dormant until CP-violation, directly linked to T-violation via the CPT theorem¹⁰, was discovered in 1964¹¹.

The interest in neutron EDM was greatly revived when a large number of theoretical models, designed to account for the CP-violation phenomenon in neutral kaon decays, predicted a neutron EDM large enough to be detected. Many ingenious technical innovations have since been implemented, and the experimental limit of neutron EDM was pushed down to $2.9 \times 10^{-26} e \cdot cm$, a six order-of-magnitude improvement over the first EDM experiment. Unlike parity-violation, the underlying physics for CP-violation remains a great enigma nearly 45 years after its discovery. Improved neutron EDM measurements will continue to provide stringent tests for various theoretical models and to help reveal the origin of CP-violation.

Table 1 lists the results from existing neutron EDM experiments. In Figure 1 the neutron EDM upper limits are plotted versus year of publication. The different symbols in Figure 1 signify different experimental techniques, which fall into three categories. The first one, which consists of only two experiments, utilizes neutron scattering to probe the effect of neutron EDM. The second and third categories both involve magnetic resonance technique. In the presence of a strong external electric field, a finite neutron EDM would cause a shift of the magnetic resonance frequency. From 1950 to mid 1970's, thermal or cold neutron beams have been used for the measurements (category II). Since early 1980's, all neutron EDM experiments have utilized ultra-cold neutrons (UCNs), which provide the most sensitive measurements to date (category III).

2.1. Neutron EDM from neutron scattering

The upper limit of the neutron EDM was first determined in 1950 by Purcell and Ramsey² from an analysis of earlier experiments of neutron-nucleus scattering^{12,13}. In these experiments, the strength of neutron-electron interaction was deduced from the interference between the neutron-nucleus and neutron-electron scattering. If the

observed neutron-electron interaction strength is attributed entirely to the neutron EDM (d_n), an upper limit of $d_n \leq 3 \times 10^{-18} e \cdot \text{cm}$ is obtained.

Another technique to search for the neutron EDM is the Bragg reflection of thermal neutrons from a single crystal. The scattering amplitude of thermal neutrons comes mainly from the nuclear interaction. However, the Coulomb field exerted by the positively charged nucleus on the incident neutron can provide additional contributions. First, it produces an effective magnetic field of $\vec{v} \times \vec{E}$ in the neutron rest frame. The neutron magnetic moment interacts with this magnetic field and leads to the Schwinger scattering. The effect of Schwinger scattering is maximal when the neutron polarization is perpendicular to the scattering plane. If the neutron has a non-zero EDM, the Coulomb field of the nucleus would lead to an additional potential $V_d(r) = -\vec{d}_n \cdot \vec{E}(r)$, where \vec{d}_n is the neutron EDM. The effect of the neutron EDM is maximal when the neutron polarization lies on the scattering plane. This feature allows the isolation of the EDM effect from the Schwinger scattering.

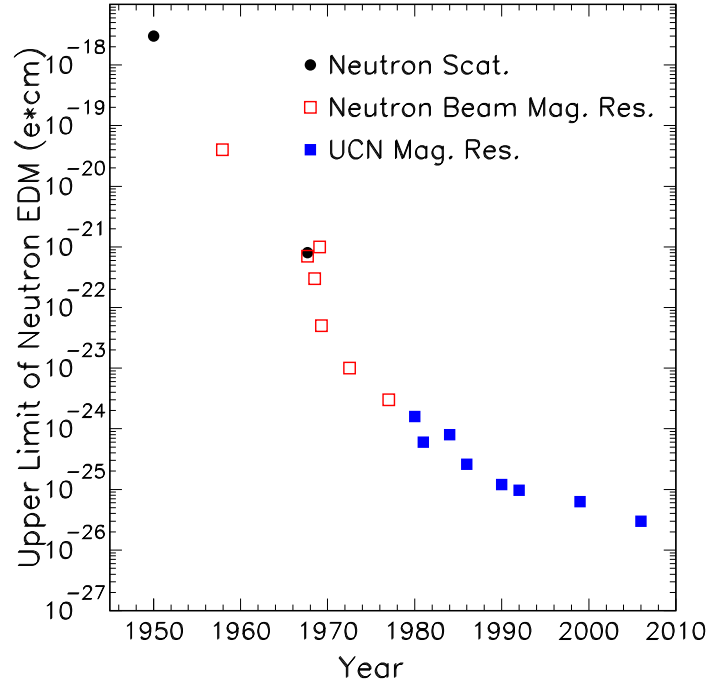


Fig. 1. Upper limits of neutron EDM plotted as a function of year of publication.

Table 1. Summary of neutron EDM experiments.

Exp. Type (Lab, year)	$\langle v \rangle$ (m/sec)	E (KV/cm) B (Gauss)	Coh. time (second)	EDM ($e \cdot cm$)
Scattering (ANL, 1950) ^{2,13}	2200	$\sim 10^{15}$ -	$\sim 10^{-20}$	$< 3 \times 10^{-18}$
Beam Mag. Res. (ORNL, 1957) ⁴	2050	71.6 150	0.00077	$(-0.1 \pm 2.4) \times 10^{-20}$ $< 4 \times 10^{-20}$ (90% C.L.)
Beam Mag. Res. (ORNL, 1967) ¹⁷	60	140 9	0.014	$(-2 \pm 3) \times 10^{-22}$ $< 7 \times 10^{-22}$ (90% C.L.)
Bragg Reflection (MIT, 1967) ¹⁴	2200	$\sim 10^9$ -	$\sim 10^{-7}$	$(2.4 \pm 3.9) \times 10^{-22}$ $< 8 \times 10^{-22}$ (90% C.L.)
Beam Mag. Res. (ORNL, 1968) ¹⁸	130	140 9	0.00625	$(-0.3 \pm 0.8) \times 10^{-22}$ $< 3 \times 10^{-22}$
Beam Mag. Res. (BNL, 1969) ²¹	2200	50 1.5	0.0009	$< 1 \times 10^{-21}$
Beam Mag. Res. (ORNL, 1969) ¹⁹	115	120 17	0.015	$(1.54 \pm 1.12) \times 10^{-23}$ $< 5 \times 10^{-23}$
Beam Mag. Res. (ORNL, 1973) ²⁰	154	120 14	0.012	$(3.2 \pm 7.5) \times 10^{-24}$ $< 1 \times 10^{-23}$ (80% C.L.)
Beam Mag. Res. (ILL, 1977) ²³	154	100 17	0.0125	$(0.4 \pm 1.5) \times 10^{-24}$ $< 3 \times 10^{-24}$ (90% C.L.)
UCN Mag. Res. (PNPI, 1980) ²⁵	≤ 6.9	25 0.028	5	$(0.4 \pm 0.75) \times 10^{-24}$ $< 1.6 \times 10^{-24}$ (90% C.L.)
UCN Mag. Res. (PNPI, 1981) ²⁶	≤ 6.9	20 0.025	5	$(2.1 \pm 2.4) \times 10^{-25}$ $< 6 \times 10^{-25}$ (90% C.L.)
UCN Mag. Res. (ILL, 1984) ²⁸	≤ 6.9	10 0.01	60-80	$(0.3 \pm 4.8) \times 10^{-25}$ $< 8 \times 10^{-25}$ (90% C.L.)
UCN Mag. Res. (PNPI, 1986) ²⁷	≤ 6.9	12-15 0.025	50-55	$-(1.4 \pm 0.6) \times 10^{-25}$ $< 2.6 \times 10^{-25}$ (95% C.L.)
UCN Mag. Res. (ILL, 1990) ³²	≤ 6.9	16 0.01	70	$-(3 \pm 5) \times 10^{-26}$ $< 12 \times 10^{-26}$ (95% C.L.)
UCN Mag. Res. (PNPI, 1992) ²⁹	≤ 6.9	12-15 0.018	70-100	$(2.6 \pm 4.5) \times 10^{-26}$ $< 9.7 \times 10^{-26}$ (90% C.L.)
UCN Mag. Res. (ILL, 1999) ³⁶	≤ 6.9	4.5 0.01	120-150	$(-1 \pm 3.6) \times 10^{-26}$ $< 6.3 \times 10^{-26}$ (90% C.L.)

Shull and Nathan¹⁴ measured Bragg reflection of polarized neutrons off a CdS crystal, and they obtained an upper limit for the neutron EDM as $5 \times 10^{-22} e \cdot cm$. An important limitation of the crystal reflection method is the difficulty to align the crystal orientation along the polarization direction of the incident neutrons. Any residual misalignment would allow the Schwinger scattering to contribute in a fashion similar to neutron EDM. The limit on d_n of the Shull and Nathan experiment is consistent with an misalignment angle of 1.6 ± 1.0 milliradian.

2.2. Neutron EDM from *in-flight* neutron magnetic resonance

The method used in this type of measurements is the magnetic resonance technique invented by Alvarez and Bloch¹⁵. For transversely polarized neutrons traversing a region of uniform magnetic field \vec{B}_0 and an electric field \vec{E}_0 parallel to \vec{B}_0 , the

precession frequency (ν) is given by

$$h\nu = -2\mu B_0 - 2d_n E_0, \quad (1)$$

where μ is the neutron magnetic moment and d_n the neutron EDM. Upon reversal of the electric field direction, the precession frequency will shift by

$$h\Delta\nu = -4d_n E_0. \quad (2)$$

Therefore, the neutron EDM can be determined as

$$d_n = -\frac{h\Delta\nu}{4E_0}. \quad (3)$$

The neutron precession frequency can be accurately measured using the technique of separated oscillatory field developed by Ramsey¹⁶. Oscillating magnetic fields of identical frequency are introduced at each end of a homogeneous-field region. Spin-flip transitions are maximally induced when the frequency of the oscillatory field is set at the resonance frequency corresponding to the neutron precession frequency. The neutron EDM is determined from the shift of the resonance frequency when the direction of the electric field is reversed.

Following the pioneering work of Purcell et al. at Oak Ridge in 1950^{3,4}, various improvements of the experimental techniques have been introduced and similar experiments were carried out at Oak Ridge^{17,18,19,20}, Brookhaven²¹, Bucharest²², Aldermaston, and Grenoble²³. Table 1 lists some characteristics of these experiments. The 1977 measurement²³ at the Institut Laue-Langevin (ILL) represented a four order-of-magnitude improvement in sensitivity over the original Oak Ridge experiment. This was accomplished by minimizing the statistical and systematic errors. The statistical uncertainty in d_n is:

$$\Delta d_n \propto \langle v \rangle / [E_0 L P (\phi_n t)^{1/2}]. \quad (4)$$

To obtain maximal sensitivity with a given running time t , the experiment needs to maximize the electric field E_0 , the distance L between the RF coils, the neutron polarization P , and the neutron flux ϕ_n . In addition, the mean neutron velocity $\langle v \rangle$ needs to be minimized. Table 1 lists these parameters for various experiments.

Many sources of systematic errors have been identified. The $\vec{v} \times \vec{E}$ effect, also called the motional field effect, refers to the additional magnetic field \vec{B}_m viewed from the neutron rest frame,

$$\vec{B}_m = \frac{1}{c} \vec{v} \times \vec{E}_0, \quad (5)$$

where \vec{v} is the neutron velocity in the lab frame. If the electric field \vec{E}_0 is not completely aligned with the magnetic field \vec{B}_0 , then \vec{B}_m would acquire a non-zero component along the direction of \vec{B}_0 . For a cold neutron of 100 m/sec, a misalignment angle of 1.5×10^{-3} radians would lead to an apparent neutron EDM of $10^{-23} e \cdot cm$.

As shown in Table 1, the most sensitive neutron beam experiment²³ obtained $d_n < 3 \times 10^{-24} e \cdot cm$ with a systematic error of $1.1 \times 10^{-24} e \cdot cm$. The dominant

contribution to the systematic error is the $\vec{v} \times \vec{E}$ effect, even though the misalignment angle is smaller than 1.1×10^{-4} radians. The limitations from the $\vec{v} \times \vec{E}$ effect and from the magnetic field fluctuation can be removed by using bottled UCN together with a comagnetometer, to be discussed next.

2.3. Neutron EDM with ultra-cold neutrons

There are two major limitations in the search for neutron EDM using thermal or cold neutron beams. First, the $\vec{v} \times \vec{E}$ systematic effect imposes stringent requirements on the alignment of the \vec{E} and \vec{B} fields, as discussed earlier. Second, the transit time of neutron beams in the magnetic spectrometer is relatively short, being $\sim 10^{-2}$ seconds. These limitations are responsible for the fact that the best upper limit for neutron EDM achieved with the cold neutron beam at ILL is $3 \times 10^{-24} e \cdot cm$, even though the statistical uncertainty is at a lower level of $\sim 3 \times 10^{-25} e \cdot cm$.

In 1968 Shapiro first proposed²⁴ using UCN in searches for neutron EDM. The much lower velocities of UCNs will clearly suppress the $\vec{v} \times \vec{E}$ effect. The amount of suppression is further enhanced in an UCN bottle which allows randomization of the neutron momentum directions. Another important advantage is that the coherence time of UCN in a storage bottle will be of the order $10^2 - 10^3$ seconds, a factor of $10^4 - 10^5$ improvement over the neutron beam experiments. This significantly improves the sensitivity for EDM signals relative to systematic effects. An important price to pay, however, is the much lower flux for UCN relative to that of cold neutron beams. A series of neutron EDM experiments using UCN have been carried out at the Petersburg Nuclear Physics Institute (PNPI) and at the ILL.

2.3.1. Measurements at PNPI using UCN

Immediately following Shapiro's proposal²⁴, preparation for an UCN neutron EDM experiment started at PNPI. The early version of the experiment^{25,26}, used a "flow-through" type spectrometer with separated oscillating fields. A 150 cm^3 liquid hydrogen moderator was used for UCN production, and a constant magnetic field of 28 mG and an electric field of $\sim 25 \text{ kV/cm}$ were applied to the double-chamber of ~ 20 liters each. From four different sets of measurements, they obtained $d_n = (2.3 \pm 2.3) \times 10^{-25} e \cdot cm$. At 90% confidence level, $|d_n| < 6 \times 10^{-25} e \cdot cm$.

Major modifications for the PNPI experiment were reported²⁷ in 1986. Probably influenced by the ILL stored UCN experiment²⁸ reporting a confinement time of ~ 60 seconds, the PNPI group modified their spectrometer to allow prolonged confinement of the UCNs. They achieved a confinement time of ~ 50 seconds. The result of this experiment was $d_n = -(1.4 \pm 0.6) \times 10^{-25} e \cdot cm$, implying $|d_n| < 2.6 \times 10^{-25} e \cdot cm$ at 95% confidence level.

The most recent PNPI measurement was reported in 1992^{29,30}. The result is $d_n = [2.6 \pm 4.0(\text{stat.}) \pm 1.6(\text{syst.})] \times 10^{-26} e \cdot cm$, which corresponds to $|d_n| < 1.1 \times 10^{-25} e \cdot cm$ at 95% confidence level. Systematic errors appeared to limit the

sensitivity of this experiment to few times $10^{-26} e \cdot cm$.

2.3.2. Measurements at ILL using UCN

Following the completion of the neutron EDM measurement²³ using the neutron beam magnetic resonance method, the interest at ILL shifted to the use of UCN³¹. Unlike the PNPI group, the ILL group started out with the UCN storage bottle technique and did not use the flow-through technique. The first ILL result was published in 1984²⁸, which demonstrated the feasibility of measuring neutron EDM with stored UCN.

The sensitivity of the ILL measurement was significantly improved in a subsequent experiment reported in 1990³². A new neutron turbine³³ increased the UCN flux by a factor of 200 and a density of 10 UCN per cm^3 was achieved in the neutron bottle. The electric field was raised to 16 kV/cm and the leakage current was reduced from 50 nA to 5 nA. Following a three-year running over 15 reactor cycles, the result was reported to be $d_n = -(3 \pm 5) \times 10^{-26} e \cdot cm$, implying $|d_n| < 1.2 \times 10^{-25} e \cdot cm$ at the 95 % confidence level.

To overcome the systematic uncertainty caused by magnetic field fluctuations in the UCN bottle, Ramsey suggested³⁴ the use of comagnetometers for EDM experiments. The idea was to store polarized atoms simultaneously in the same bottle as the neutrons. Fluctuation of the magnetic field will affect the spin precession of the comagnetometer atoms, which can be monitored. The ILL collaboration selected ^{199}Hg as the comagnetometer. Effects from the ^{199}Hg EDM are negligible, since experiment³⁵ showed that the EDM of ^{199}Hg was less than $2.1 \times 10^{-28} e \cdot cm$.

In 1991, an ILL experiment³⁶ used a 20-liter UCN bottle containing $3 \times 10^{10}/cm^3$ polarized ^{199}Hg . The UCN coherence time was 130 seconds, roughly a factor of two improvement over previous experiment. However, the maximum electric field in this UCN bottle is only 4.5 kV/cm, roughly a factor of 3.5 lower than before. The UCN flux also appeared to be a factor of 4 lower than in the earlier experiment. Data were collected over ten reactor cycles of 50 days' length, and the ^{199}Hg comagnetometer was shown to reduce effects from magnetic field fluctuations significantly. The result of this experiment was $d_n = (1.9 \pm 5.4) \times 10^{-26} e \cdot cm$. An upper limit on the neutron EDM of $|d_n| < 9.4 \times 10^{-26} e \cdot cm$ was obtained at 90% confidence level. When this result was combined with the result from the earlier ILL experiment³², an improved upper limit of $6.3 \times 10^{-26} e \cdot cm$ was obtained.

The most recent ILL experiment³⁷ reached a higher E field of 10 KV/cm by adding 10^{-3} torr of helium gas to prevent spark. An important systematic effect due to geometric phase, which arises when the trapped particles experience a magnetic field gradient $\partial B_z/\partial z$, was identified³⁸ and corrected for. The upper limit of neutron EDM is now pushed down to $2.9 \times 10^{-26} e \cdot cm$ at 90% confidence level.

The ILL experiments demonstrated the advantage of using a comagnetometer for reducing a dominant source of systematic error. It is conceivable that the sensitivity on neutron EDM can be further improved if more intense UCN flux together with

a suitable comagnetometer become available. New experiments have been proposed at ILL and the SNS using UCN produced in superfluid ^4He , as discussed in the next Section.

3. Future Neutron EDM Experiments

Several new neutron EDM experiments aiming at improved sensitivities have been proposed³⁹. To achieve a greater statistical accuracy, it is important to increase the UCN flux, the electric field strength, and the UCN storage time. Golub and Pendlebury⁴⁰ first suggested that higher UCN flux/density can be obtained using the down-scattering processes, where a fraction of an intense cold neutron beam scatter inelastically from a suitable material and lose practically all their energies to become UCNs. An intense UCN source based on down-scattering process in solid deuterium has been constructed at Los Alamos⁴¹, and another one is being constructed⁴² at the Paul-Scherrer Institute (PSI).

A different technique⁴³ using superfluid helium has also been utilized to produce intense UCNs stored in bottles⁴⁴. The energy-momentum dispersion curves for He-II and free neutrons intersect at the neutron momentum of $\sim 8.9 \text{ \AA}$. Therefore, monochromatic neutron beam at this momentum can efficiently produce UCNs by exciting phonons in He-II. An EDM experiment using UCN produced in superfluid helium has several important advantages. First, a high electric field can be applied due to the high dielectric constant of liquid helium. Second, more uniform magnetic field can be obtained with superconducting shields. Finally, the storage time can be much improved since the loss from wall-scattering is greatly reduced due to the low temperature of the walls.

In order to benefit from the projected improvement in statistical accuracy for future neutron EDM experiments, systematic uncertainties have to be reduced accordingly. Most of the systematic uncertainties are related to the stability and uniformity of the magnetic fields. As discussed later, various schemes of active and passive magnetometers, as well as co-magnetometers have been proposed for future neutron EDM experiments. We now describe the main features and status of these future neutron EDM experiments.

3.1. Room Temperature Experiments at PSI and ILL

A new experiment⁴⁵ based on the Sussex-RAL-ILL apparatus has been proposed at PSI. This new experiment plans to use the high intensity UCN source currently being constructed at PSI⁴². This UCN source is expected to deliver UCN densities of $\sim 1000 \text{ per cm}^3$ to the EDM experiment, roughly two orders of magnitude better than the existing ILL experiment.

Extensive R&D efforts are underway to study various schemes for improving the apparatus. An array of laser-pumped Cs magnetometers⁴⁶ placed near the UCN cell will monitor the magnetic field and its gradients. These magnetometers could provide inputs for the correction coils to actively stabilize the magnetic field and mini-

mize the field gradients. The sensitivity of the ^{199}Hg co-magnetometer could also be improved, possibly from a sensitivity of 200 femto-Tesla to 40 femto-Tesla⁴⁷. Addition of a second co-magnetometer such as ^3He and ^{129}Xe has also been considered. Since different co-magnetometers have different sensitivities to the geometric-phase effect, the additional co-magnetometer could help to isolate this effect³⁹.

Using the improved version of the Sussex-RAL-ILL apparatus together with the intense PSI UCN source, it is anticipated that a sensitivity of $5 \times 10^{-27} e \cdot \text{cm}$ can be reached after data-taking during 2009-2010. Meanwhile, a design of a new apparatus is underway, which can lead to a factor of 10 improvement in sensitivity due to a larger experimental volume, an improvement in the electric field strength, a better match to the UCN source, and a longer running time. Data-taking for this new apparatus is planned for 2011-2014³⁹.

Another room-temperature UCN experiment, led by the PNPI group, will use an apparatus consisting of 4 back-to-back measurement chambers with opposite electric fields. This design allows cancellation of some systematic errors. A total of 16 Cs magnetometers will be used for magnetic field stabilization. The experiment plans to use the UCN source at ILL to reach a sensitivity of $10^{-27} e \cdot \text{cm}$.

3.2. ILL Cryogenic Experiment

A CryoEDM experiment by the Sussex/RAL/Oxford/Kure/ILL collaboration is being installed at ILL⁴⁸. UCNs will be produced in superfluid ^4He cell with cold neutron beam. Production of UCN with this technique has been demonstrated⁴⁹ at ILL. A 400 KV high voltage supply will be connected to the HV electrode. The holding field B_0 will increase by a factor of 5 over the latest ILL experiment to reduce the geometric-phase effect, which is proportional to $1/B_0^2$. Neutrons will be detected using ^6LiF -coated silicon solid-state detectors⁵⁰ placed inside the 0.5 K He-II liquid via the $n + ^6\text{Li} \rightarrow ^3\text{H} + ^4\text{He}$ reaction.

Since ^{199}Hg co-magnetometer can not function at low temperature, alternative techniques are required to monitor the magnetic field. An axial shielding factor of $\sim 10^6$ will be obtained from mu-metal, superconducting, and active shieldings. An array of 12 pickup loops for a SQUIDS system are placed behind the grounded electrodes to monitor the magnetic fields. A control cell adjacent to the measurement cell will have no applied electric field and act as a neutron magnetometer.

This experiment expects to obtain a statistical sensitivity of $\sim 10^{-27} e \cdot \text{cm}$ around end of 2008. With further improvement of the apparatus and a new beam line at ILL with six times higher intensity of 8.9 A neutrons, a sensitivity of $\sim 2 \times 10^{-28} e \cdot \text{cm}$ is anticipated after two to three years of running.

3.3. SNS nEDM experiment

The nEDM experiment^{51,52}, based on the idea outlined by Golub and Lamoreaux⁵³ in 1994, will run at the 8.9 Å Fundamental Neutron Physics Beamline (FNPB) at the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory. The

schematics of the proposed apparatus is shown in Figure 2. Like the ILL CryoEDM experiment, superfluid ^4He will be used to produce and trap the UCNs. However, a major difference for the nEDM experiment is the use of polarized ^3He as a comagnetometer as well as a spin analyser.

In the proposed neutron EDM experiment, a small concentration of polarized ^3He atoms ($X \sim 10^{-10}$) would be introduced into the superfluid to serve as a comagnetometer. The ^3He atoms would also function as a highly sensitive spin analyzer due to the large difference between the n - ^3He absorption with total spin $J = 0$ compared to $J = 1$. The absorption reaction $n + ^3\text{He} \rightarrow p + ^3\text{H}$ releases 764 keV of total kinetic energy. This recoil energy excites short-lived molecules in the superfluid ^4He which emit ultraviolet scintillation light. Consequently, the observed rate of scintillations depends on the relative angle between the UCN and ^3He spins. In a transverse magnetic field B_0 , the UCN and ^3He spins will precess at their respective Larmor frequencies: $\omega_n = \gamma_n B_0$, and $\omega_3 = \gamma_3 B_0$ where γ_i is the gyromagnetic ratio of each species. If the ^3He and UCN spins are parallel at time $t = 0$, a relative angle between the spins develops over time because the ^3He magnetic moment is larger than that of the neutron ($\gamma_3 \approx 1.1 \gamma_n$). In the presence of a static electric field E parallel to B_0 , the rate of scintillations observed is modulated at the difference of the two spin precession frequencies:

$$\omega_{\text{rel}} = (\gamma_3 - \gamma_n)B_0 + 2d_n E/\hbar. \quad (6)$$

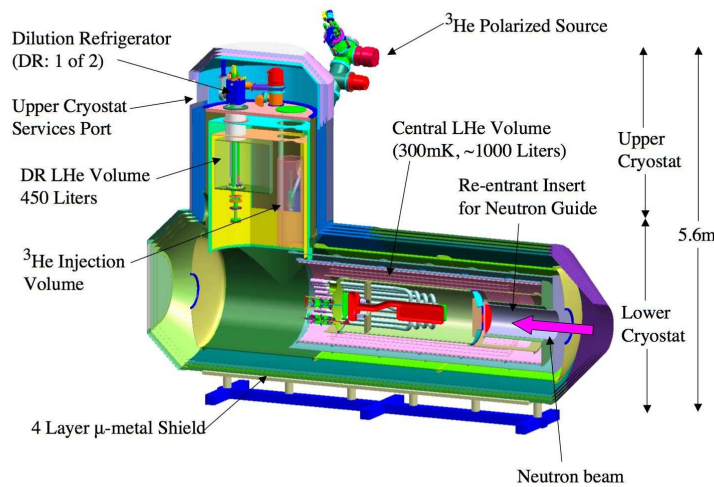


Fig. 2. Schematics of the SNS nEDM apparatus.

Eq. 6 shows that ω_{rel} depends only on $d_n E$ in the limit of $B_0 \rightarrow 0$. Alternatively, the experimental signal would become independent of B_0 if the condition $\gamma_3 - \gamma_n = 0$ were satisfied. Spurious signals due to inhomogeneity or slow drifts in the magnetic fields would thereby be eliminated. The UCN and ^3He magnetic moments can be modified, and in fact equalized, by the dressed spin effect^{53,54} in which a particle's effective magnetic moment is modified by applying an oscillating magnetic field $B_d \cos \omega_d t$ perpendicular to B_0 . In the weak-field limit ($B_0 \ll \omega_d/\gamma$), the dressed magnetic moment γ'_i is given by

$$\gamma'_i = \gamma_i J_0(x_i), \quad x_i \equiv \gamma_i B_d / \omega_d, \quad (7)$$

where J_0 is the zeroth-order Bessel function. Using this expression, one can solve for the “critical” dressing field magnitude which makes $\gamma'_n = \gamma'_3$. If this critical dressing field is applied, corresponding to $x_3 = 1.32$, the relative precession between the UCN and ^3He (Eq. 6) vanishes except for the contribution from $d_n E$.

Extensive R&D effort has been underway. In particular, the distribution of ^3He in superfluid ^4He and the ^3He diffusion coefficient at temperature below 1 K have been measured^{55,56,57}. The dielectric strength of superfluid helium has been studied using a prototype test apparatus⁵⁸. The relaxation of polarized ^3He in a mixture of ^3He and ^4He at a temperature below the λ point has been investigated⁵⁹. A study of the dressed-spin effect has been carried out using a cold atomic ^3He source of 99.5% polarization constructed for the nEDM experiment⁶⁰. Optimization of the neutron beam line has also been carried out⁶¹.

The FNPB is currently under construction and is scheduled to be completed in 2010. The construction of the nEDM experiment is expected to begin in 2009. The goal is a two order-of-magnitude improvement in sensitivity over the present limit.

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